HeatWatch: Identification of Parameters Influencing the Urban Heat Island Effect through Deep Learning Techniques

Murat Kılınç [1], Can Aydın [2], Gizem Erdoğan Aydın [3], Damla Balcı [4]
[1] Manisa Celal Bayar University, Computer Research and Application Center, 45140 Manisa, Turkey – kilinc.murat@cbu.edu.tr
[2] Dokuz Eylul University , Dept. of Management Information System, İzmir, Turkey- can.aydin@deu.edu.tr
[3] University of İzmir Demokrasi, Dept. of Urban and Regional Planning, İzmir, Turkey – gizem.erdogan@idu.edu.tr
[4]University of İzmir Demokrasi, Dept. of Urban and Regional Planning, İzmir, Turkey – damla.balci@idu.edu.tr

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Abstract

Global climate change (GCC) is accelerated by factors such as greenhouse gas emissions from human activities and the urban heat island (UHI) effect, particularly in densely urbanized areas. According to the WMO's 2023 data, GCC warming effects increased by 49% from 1990s to 2021, 80% of this increase was due to CO2. Furthermore, average global temperatures have increased by 1.1°C since the early 1900s. In this respect, the urban heat island (UHI) effect has gained importance with global temperatures. Environmental problems that cause cities to be warmer than rural areas, especially due to hard ground surfaces, building density and decreasing green areas, have the potential to create negative impacts on human health. Therefore, it is important to identify and manage the impact of UHI. This is because traditional methods are limited to fixed station data, but technologies such as remote sensing and geographic information systems (GIS) provide more comprehensive results for this management. In an innovative approach, deep learning and artificial intelligence techniques can provide more accurate analysis by processing large datasets. In this context, this research proposes a conceptual framework for using deep learning techniques to detect the UHI effect with data obtained from street images and unmanned aerial vehicles. With the proposal, the UHI value will be calculated by detecting objects such as trees, air conditioners, vehicles and building cladding with the YOLO-Real-Time Object Detection algorithm. With this approach, it is aimed to obtaining more precise and accurate results in determining the UHI effect. In addition, a web-based management panel will be designed for managers to review the results and use them in decision-making mechanisms. It is aimed at disseminating this model and making it an important tool in the planning of urban areas.

1. Introduction

Global climate change has become one of the most important environmental problems today. Especially in areas with dense urbanization, factors such as greenhouse gas emissions from human activities and the urban heat island (UHI) effect accelerate climate change. According to the World Meteorological Organization's (WMO) 2023 data, greenhouse gas warming effects increased by 49% from the 1990s to 2021; 80% of this increase was due to carbon dioxide (CO2). At the same time, average global temperatures have increased by 1.1°C since the early 1900s. This has made the environmental impacts of urbanization and human activities even more pronounced (Klein & Anderegg, 2021; Singh & Purohit, 2014).

The UHI effect is a phenomenon that occurs as a result of dense urbanization and causes city centers to be warmer than their rural counterparts. This temperature difference is the result of surfaces such as asphalt and concrete replacing natural surfaces, which absorb more heat and reflect less. The urban heat island effect can increase energy consumption, reduce air quality and generally negatively affect the health of city dwellers. Furthermore, the increase in temperature in urban areas leads to increased use of air conditioners and thus higher energy consumption, which in turn increases greenhouse gas emissions, further accelerating climate change. A better understanding and management of these impacts is critical for sustainable urban planning (Zhang et al., 2020). The aim of this study is to examine the role of deep learning and image processing techniques in identifying and analyzing the UHI impact. In this context, in addition to traditional methods, advanced technologies such as remote sensing and geographic information systems (GIS) and images obtained from street images and unmanned aerial vehicles (UAVs) are used to determine the UHI impact more comprehensively. Deep learning algorithms have the potential to predict the spatial and temporal variations of UHI impact with high accuracy by processing large data sets (Oh et al., 2020). In particular, real-time object detection algorithms such as YOLO (You Only Look Once) can play an important role in determining the UHI impact by identifying different types of surfaces in cities, such as green spaces, water bodies, buildings and roads (Lavanya & Pande, 2023; Sami et al., 2023).

In this context, the surface temperatures and their distribution in urban areas need to be analyzed in detail by using a combination of satellite imagery and video streaming data (Verma et al., 2021). Furthermore, it is aimed at guiding urban planners and decision makers by developing recommendations to reduce the UHI impact. In particular, strategies such as green roofs, green spaces and reflective surfaces are among the potential solutions to reduce the UHI impact. In conclusion, this study aims to demonstrate the potential of deep learning and image processing techniques in identifying and managing the urban heat island effect. The effective use of these technologies can make significant contributions to the planning and development of sustainable and climate-friendly cities. In this framework, it will be possible to analyze the current situation and develop data-based strategies for future planning.

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On the other hand, the impacts of the GCC on cities are not limited to temperature increases. Extreme weather events are becoming more frequent and more severe. For example, extreme rainfall and storms can lead to flooding and inundation when urban infrastructure is inadequate. Such events can cause both economic losses and serious damage to human health. Therefore, effective measures need to be taken for cities to adapt and become resilient to climate change. Protecting biodiversity in urban areas is also an important factor in combating climate change. Green spaces and parks not only reduce the impact of UHI, but also increase biodiversity by supporting local ecosystems. These locations help lower the atmospheric concentration of carbon dioxide by supporting plants that have the ability to sequester carbon. The design and planning of green infrastructure is also crucial for water management and air quality improvement.

Overall, the conceptual framework presented in this study aims to provide urban planners, policy makers and researchers with feasible strategies to mitigate the UHI impact and other negative impacts of climate change. The integration of deep learning and image processing techniques can bring innovative solutions to existing problems and contribute to making cities more resilient to future climate change scenarios. In this context, interdisciplinary collaborations and technological innovations play an important role in sustainable urbanization and climate change adaptation.

2. Literature Review

2.1 Traditional Methods for Determining Urban Heat Island Effect

Traditional methods for determining and analyzing the urban heat island effect are usually limited to data from fixed stations. These methods determine temperature differences between urban and rural areas using temperature data collected from meteorological stations. These stations measure environmental temperatures through thermometers placed at specific locations and record this data at regular intervals (Sun, Kato, and Gou 2019). This method is useful for establishing an overall temperature trend but is insufficient to examine microclimate changes in detail. Data from fixed stations are often not representative of large areas and do not reflect local temperature variations (Xie and Zhang 2016). These stations are usually located in the central areas of the city or at certain critical points. However, just as there can be temperature differences between different areas in a city, microclimate differences can also be observed at different points in the same region. For instance, the information provided by fixed stations might not appropriately reflect the temperature difference between a parking lot and the nearby asphalt road.

Another limitation of traditional methods is that these stations often cannot cover entire urban areas. Given the size and complexity of cities, it is not possible to position a few fixed stations to cover the entire city. This prevents a homogeneous measurement of the urban heat island effect, especially in large and dense cities. Data obtained from meteorological stations may also vary depending on weather conditions. For example, factors such as wind direction and speed, cloud cover, humidity can directly affect temperature measurements. This has the potential to make it difficult to accurately determine the UHI effect. Consequently, although traditional methods provide a basic starting point for determining UHI impact given the limitations of these methods, additional techniques and methodologies need to be used for more detailed and comprehensive analyses. Advanced technologies such as remote sensing techniques and geographic information systems (GIS) developed in recent years make it possible to obtain more comprehensive and accurate results to overcome such limitations. These new approaches allow the UHI impact to be studied in more detail and from a broader perspective, helping urban planners and environmental scientists to make more informed decisions.

2.2 Remote Sensing and Geographic Information Systems (GIS)

The majority of studies found in the literature use satellite imagery and remote sensing. Examining research that employs image processing methods reveals that satellite images are frequently employed and typically conducted as surface urban heat island (SUHI) studies. Many studies (Nichol, 1996; C. Yin, Yuan, Lu, Huang, & Liu, 2018) employ land surface temperature from thermal satellite photos to estimate urban heat islands. Different surface temperatures and the urban heat island effect in Cluj, Romania were analyzed using GIS techniques using satellite photos in a study carried out by Imbroane et al. (2014). In the study where surfaces with temperatures higher than 30 degrees Celsius were identified, it was observed that green areas and water bodies had the coldest surface temperature and this temperature was 8-10˚C lower than civil and industrial areas (Imbroane et al., 2014). In a different study, Furuya et al. used machine learning techniques to detect urban heat islands in 2023 using data from Landsat 8 for land surface temperature, the official census for socioeconomic variables, and Sentinel-2 and Planet images for environmental variables. The study employed six different algorithms to estimate the land surface temperature. Of these, the decision tree method produced the best prediction results, with $r = 0.96$, $MAE = 1.49$, and $RMSE = 1.88$. It is emphasized that the data from the study could be useful in the development of smart cities (Furuya et al., 2023).

An artificial neural network technique was employed in a different study by Mokarram et al. in (2023) to look into the effects of urbanization in the northern part of Iran in relation to urban heat islands. In the study, Markov chain was also utilized to predict thermal pollution, and MODIS pictures from 2001, 2010 and 2019 were used to determine vegetation levels and climatic parameters. While enormous areas can be observed with satellite images, thorough analyses requiring high-resolution data are limited in some aspects. The limited resolution of satellite imagery can lead to the loss of micro-details and cause many factors to be ignored. This may lead to incomplete or inadequate evaluation of the parameters used in the determination of the urban heat island effect.

Okumuş (2022) brought attention to the issues caused by the low resolution of satellite photos, such as losing features and neglecting numerous aspects. According to the study, satellite imaging has limitations, particularly when it comes to identifying small-scale urban heat island impacts, and is insufficient for correctly measuring surface temperatures. In addition, the diversity and accuracy of the parameters used in analyses based on satellite imagery may affect the reliability of the results obtained. These limitations of satellite imagery

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necessitate the use of alternative data sources and methods. By using detailed street-scale data to identify and analyse the urban heat island (UHI) effect, it is possible to obtain more detailed and reliable results in UHI studies. In UHI investigations, more precise and trustworthy results can be obtained by identifying and analyzing the urban heat island (UHI) effect using comprehensive street-scale data. Furthermore, these technologies can make it possible to do analyses with greater thoroughness and to account for additional parameters.

In summary, while satellite imagery-based research enables quick scanning of vast regions, thorough and precise analysis necessitates the employment of different high-resolution data sources and techniques. This will make it possible to manage the impact of UHI more precisely and thoroughly.

2.3 Deep Learning and Image Processing Techniques

Deep learning and artificial intelligence techniques have significant potential in determining the UHI effect (Chun & Guldmann, 2014; G. Guo, Zhou, Wu, Xiao, & Chen, 2016). These techniques can better analyse the heat island effect in urban areas by processing large datasets and providing more accurate results. Artificial intelligence techniques have the capacity to evaluate a wider range of parameters, overcoming the limitations of traditional methods. Thus, it is possible to analyse the UHI effect in a more holistic and detailed manner.

Many academics have attempted to use deep learning techniques in this context in order to identify the urban heat island effect. For example, Li et al. (2018) developed a deep learning model using remote sensing data to identify the urban heat island effect. This model took into account a number of factors, including building density and the amount of green space, and it was able to identify the urban heat island effect. By utilizing big data sets, the model was able to produce outcomes that were more trustworthy and accurate. Li et al. are an important example of how deep learning techniques can be used effectively with high-resolution data.

Similarly, a deep learning model to detect the urban heat island effect was proposed by Zhang et al. (2019). Using a variety of spatial characteristics, including land use and traffic density, this model was able to accurately calculate the urban heat island effect. Zhang et al. study demonstrates how well deep learning methods may be integrated with GIS systems, which are used for urban analysis. The model was able to analyze the urban heat island effect from a wider angle by merging several spatial data sets.

Moreover, such studies reveal how important the use of artificial intelligence techniques can be in urban planning and management processes. Deep learning models have the capacity not only to analyse the current situation but also to predict and simulate future changes. This offers a significant benefit when formulating plans to lessen the impact of the urban heat island.

To sum up, artificial intelligence and deep learning methods are particularly effective for detecting and analyzing the urban heat island effect. By employing a broader range of diverse data sources, these techniques enable a more precise and comprehensive analysis of the urban heat island effect, thereby yielding noteworthy advancements in urban management procedures. Future developments in this area will contribute to the sustainability and livability of metropolitan areas through increased research and applications.

3. HeatWatch Conceptual Framework

HeatWatch is an image processing tool that is under development in order to reveal the UHI impact parameters and to make instant UHI measurements with these parameters. This tool, in which the parameters affecting the UHI measurement are analyzed and evaluated, is presented as a conceptual framework in the study and which parameters will be included in the image processing process are explained. In this context, modern data acquisition and processing techniques have been identified in order to accurately determine and analyze the UHI effect. In particular, to overcome the resolution limitations of satellite imagery, street imagery and UAV data, which provide more detailed and high-resolution data, are preferred. In addition, image processing methods supported by deep learning and artificial intelligence techniques will enable more precise detection of the UHI effect.

3.1 Data Collection

The UHI effect will be ascertained in this study through the utilization of high-resolution imagery obtained from unmanned aerial vehicles (UAVs) and street imagery. Street imagery makes it possible to examine all of the city's buildings, roads, parks, and other structures in detail. These images provide street-level details that enable micro-level analysis of the urban environment and reveal details at street level, allowing the urban environment to be analysed at a micro level. However, UAVs obtain higher resolution imagery at lower altitudes, which makes it possible to map large areas quickly and thoroughly (Bakogiannis, Kyriakidis, and Zafeiris 2022). According to Kang et al. (2018), the information required to calculate the UHI effect is provided by the detailed models of buildings and other structures that are made using the images captured by UAVs.

3.2 Model Development with YOLO

The images to be collected within the HeatWatch conceptual framework will be analyzed using the YOLO (You Only Look Once) Real-Time Object Detection algorithm (Wan, Pang, and Lan 2022). This algorithm will be used to detect objects and features such as trees on street sections, air conditioners on building facades, vehicles parked on the road, buildings, building colors and cladding, and road pavement. The YOLO algorithm is preferred for its fast and efficient results in object detection (Gothane 2021; Lakhotiya et al. 2023). YOLO detects and classifies objects in the image using a single feed-forward neural network (Figure 1).

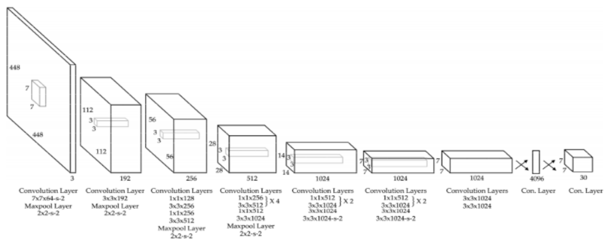

Figure 1. YOLO Network Architecture (Koylu, Zhao, ve Shao 2019; Redmon vd. 2016)

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In this way, it is possible to determine both the location and the class of detected objects at the same time. By working on high-resolution images, the algorithm can detect even small details in the city. These details include elements such as building facades, the density of green spaces, street furniture and even small vehicles. These capabilities of YOLO are critical in determining the UHI impact. The total number, surface area and location of the detected objects will be used to create an urban heat island risk map. These analyses will allow the UHI impact in different areas of the city to be determined and its change over time to be monitored. For example, the density of trees in a given area, the amount of green space, and the color and material properties of building cladding provide important data for analyzing the heat island effect (Ibrahim et al. 2018). Likewise, the material and color of road pavements are among the factors affecting surface temperatures.

The Roboflow platform plays a critical role in the data labeling phase of this process. Roboflow enables fast and efficient labeling of large datasets, saving researchers time and effort. This platform automates the labeling of images, providing researchers with a more efficient working environment. Data labeled with Roboflow can be used in the training process of the YOLO algorithm to increase the accuracy and efficiency of the model. In this context, the data labeling process is an important step in preparing images for analysis. Within the HeatWatch conceptual framework, first, street images and images collected by UAVs will be uploaded to the Roboflow platform. These images are tagged to include various objects such as trees, air conditioners, vehicles, buildings, building colors and cladding, road pavement. Thanks to Roboflow's advanced labeling tools, the positions and classes of these objects are precisely determined. The labeled data is used in the training process of the YOLO algorithm to increase the learning capacity of the model (Zhang et al. 2023). Using this labeled data, the YOLO algorithm learns to detect and classify objects in images. By working on high-resolution images, the algorithm can detect even small details in the city. These details can include elements such as building facades, the density of green spaces, street furniture and even small vehicles. These capabilities of YOLO are critical in determining the UHI impact (Mantau et al. 2022).

The total number, surface area and location of the detected objects will be used to determine the UHI effect. The findings allow us to identify the heat island effect in different areas of the city and monitor its change over time. For example, the density of trees in a given area, the amount of green space, and the color and material properties of building cladding provide important data for analyzing the heat island effect (Ibrahim et al. 2018). Similarly, the material and color of road pavements are also among the factors affecting surface temperatures (Nwakaire et al. 2020).

Furthermore, when the data obtained with the YOLO algorithm is combined with big data analytics and machine learning methods, further analysis can be performed (Kovacs-Györi et al. 2020). These analyses are not only limited to the assessment of the current situation, but also include simulations and predictions of future changes. This contributes to the development of strategies for urban planning processes. For example, using the data obtained, the possible effects of interventions such as increasing green areas in the city or changing the surface coverings of buildings on the UHI impact can be simulated. Such simulations enable urban planners and policymakers to make more effective and targeted decisions to reduce the UHI impact. This contributes to making urban areas more livable and improving the health and quality of life of people living in the city.

In conclusion, the use of the YOLO algorithm and the Roboflow platform allows for a detailed and accurate analysis of the UHI impact. This enables urban planners and policy makers to make more effective and targeted decisions to reduce the UHI impact. The integration of Roboflow and data labeling processes accelerates the training and improves the accuracy of deep learning models. This offers an innovative and effective approach to identifying and managing UHI impact. The combination of the YOLO algorithm and the Roboflow platform provides significant advantages in identifying and managing UHI impact. YOLO's fast and accurate object detection capabilities and Roboflow's efficient data labeling processes allow for micro-level inspection of urban areas. This helps to analyze and manage the UHI impact more comprehensively. Thus, contributing to the goal of urban planners and policy makers to create more livable and sustainable urban areas.

3.3 Data Analysis and Visualization

Managing and visualizing the collected data is a critical part of the analysis process. Mapping the UHI impact and monitoring changes over time can help urban planners and policymakers make more informed decisions. In this context, the development of a user-friendly management panel ensures that the data is analyzed effectively and the results are presented in an understandable way. The HeatWatch management panel to be developed in this context will include functions such as visualizing the detected objects and features, mapping the heat island effect and creating detailed reports of the analysis. This will make it easier for urban planners to understand the UHI impact and develop strategies to mitigate these impacts. Also, this dashboard will make it possible to share the data obtained with different stakeholders and increase collaboration.

4. Results and Discussion

The existence of population in urban areas increases building densities, reduces the existence of green areas, especially in developing countries, and increases pressure on the natural environment. In addition to construction stress, intensive use of materials such as asphalt and cement and diversity in land use decisions cause an increase in surface temperatures. For these reasons, environmental temperatures are significantly higher in urban centres than in rural areas. This situation is called the UHI effect. The UHI effect can cause significant environmental and health problems for people living in cities. Thus, it is crucial to determine and manage the impact of UHI.

The urban heat island (UHI) effect can lead to higher energy consumption, poorer air quality, and overall worse health outcomes for urban populations, particularly in densely populated areas. The UHI effect increases summertime air conditioner use, which raises energy demand in terms of energy consumption. This increases the burden on energy production and distribution, leading to higher energy costs and a faster diminishment of energy resources. Furthermore, increased energy consumption contributes to climate change by increasing greenhouse gas emissions by increasing the use of fossil fuels, causing a cycle. Low-income and vulnerable minority communities are especially vulnerable to the effects of UHI because they frequently lack access to cooling amenities like air conditioners. In this perspective, the effect of air conditioning utilisation on UHI is also among the areas that need to be evaluated. Therefore, the HeatWatch to be developed for the UHI effect is an image processing model that also detects air conditioners. UHI also has impacts on air quality. High temperatures encourage the accumulation of other pollutants, including ozone. Particularly during the summer, it might result in worse air quality and a rise in respiratory diseases. High temperatures also elevate the risk of heat stroke, dehydration, and other heat-related health problems. The elderly, children, and disadvantaged populations with chronic diseases are particularly vulnerable to the UHI, and the negative effects are serious. Soaring temperatures can increase the risk of heart attacks, strokes, and other cardiovascular diseases. Additionally, during heat waves, it is known that mortality rates rise (Heaviside, C. vd. 2016; Tan, J. 2010).

This study suggests a novel method for evaluating the impact of UHI that makes use of deep learning and image processing methods. With this approach, it is aimed at mapping and managing the UHI impact more accurately by obtaining more precise and detailed data. Different from the studies in the literature, street images and images obtained from unmanned aerial vehicles (UAVs) will be used in this study. By taking the measurements and analyses made by traditional methods one step further, it is aimed to detect the objects belonging to the parameters that will affect the urban heat island effect on the images obtained from micro-scale street images using deep learning techniques and to automatically create an urban heat island risk map.

Street photos enable a thorough, real-time examination of the city's roads, buildings, green areas, and other structures. High-resolution street photos make it possible to identify even small-scale changes in the city. This makes it possible to analyse the micro-level elements that affect the UHI impact, such as the quantity of green areas, the colours and materials of building facades, etc. This detailed street-level data helps to spatially characterise the urban heat island effect at a smaller scale and with greater precision. The tool provides data and analysis support for decision-making in building development plans and urban design projects. UAVs collect higher-resolution imagery from lower altitudes, enabling rapid and detailed mapping of large areas. Since UAVs provide higher-resolution data than conventional satellite imagery, even small details can be detected. The images obtained by UAVs are used to create detailed models of buildings and other structures, providing the necessary data for the determination of the urban heat island effect.

In this study, the images collected using the YOLO (You Only Look Once) real-time object detection algorithm will be analysed. The YOLO algorithm is preferred due to its fast and effective results in object detection. YOLO detects and classifies objects in the image using a single feed-forward neural network. In this way, it is possible to determine both the positions and the classes of the detected objects at the same time. The YOLO algorithm will be used to detect objects and features such as trees, air conditioners, vehicles, buildings, building colours and facades, and road coverage on street sections.

Values such as the total number, surface area and location of the detected objects will be used in the creation of the urban heat island risk map. These analyses allow the heat island effect in different parts of the city to be determined and its change over time to be monitored. For example, the density of trees in a given area, the determination of the area of green space and the colour and material properties of building cladding provide important data for the analysis of the heat island effect.Moreover, the material and colour of road pavements are also among the factors affecting surface temperatures. In addition, when the data obtained with the YOLO algorithm is combined with big data analytics and machine learning methods, further analyses can be performed. These analyses are not only limited to the assessment of the current situation, but also encompass simulations and forecasts of future changes. Thus, it contributes to the development of proactive strategies in urban planning processes.

For example, using the data obtained, the possible effects of interventions such as increasing green areas in the city or changing the surface coverings of buildings on the UHI impact can be simulated. By using these simulations, policymakers and urban planners can reduce the urban heat island effect by making more focused and effective decisions.Implementing strategies to reduce the impact of UHI in urban planning and design processes contributes to making urban areas more liveable and improving the health and quality of life of people living in the city. It supports urban planners and policy makers to adopt more effective strategies to mitigate the urban heat island effect.

In conclusion, the innovative approaches proposed in this study can provide significant advances in identifying and managing the urban heat island effect. The use of deep learning and image processing techniques allows for a more accurate and detailed analysis of the urban heat island effect.

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